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TECHNICAL NOTE

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FLIGHT INVESTIGATION OF PILOT'S ABILITY

TO CONTROL AN AIRPLANE HAVING POSITIVE AND NEGATIVE

STATIC LONGITUDINAL STABILITY COUPLED WITH VARIOUS

EFFECTIVE LIFT-CURVE SLOPES

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Langley Field, Va.

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SUMMARY

A flight investigation was made of an airplane having an automatic control system capable of varying static longitudinal stability and lift-curve slope. The control system operated wing flaps which were geared to a portion of the elevator and produced a variation in both the static stability and lift-curve slope of the airplane. The ability of human pilots to control the variable-stability airplane without the aid of stability augmentation was investigated at various values of positive and negative static stability and lift-curve slope.

Results of the study, based on flight data and pilot opinions, indicated that neutral or very slightly unstable static stability was tolerable in the presence of some lift capability. When the airplane was unstable and required 2 seconds or longer to diverge to double the amplitude in pitch, the pilots considered it acceptable. Divergences that doubled the pitch amplitude in less than 2 seconds were either marginal or unacceptable as the time to diverge grew shorter. A large decrease in the amount of normal acceleration per degree change in angle of attack did not change the tolerable-stability boundary for human-pilot control in terms of the dynamic response of the airplane which defined the time to diverge. A wide variation in normal acceleration per degree change in angle of attack was possible in the present tests. Human-pilot tolerance in the presence of longitudinal instability, however, limited the unstable divergence time of the airplane to 2 seconds regardless of the lift-curve slope. In the process of testing successive flight configurations to cover a range of stability conditions, negative lift-curve slopes were experienced for short periods of time in the earlier, statically stable data flights. Decreased and reversed amounts of normal acceleration per degree change in angle of attack caused pilots to classify some of these stable conditions as unsatisfactory. The pilots agreed, however, that after a period of familiarization, control of a stable airplane with a negative lift-curve slope would be acceptable.

INTRODUCTION

Existing airplane handling-qualities requirements call for positive maneuvering stability in all flight regimes and for a specific range of stable values of force per unit of acceleration depending on the airplane. These requirements for stability are based on long experience, including a history of accidents involving structural failure on some airplanes which became neutrally stable or unstable in maneuvers. These accidents can be explained on the basis that when an airplane is flying at high dynamic pressures, only a few degrees change in angle of attack may be required to exceed the allowable limit load factor; and any instability that produces an exaggerated attitude may cause the airplane to exceed its structural limits rapidly.

Recently, interest has increased in the ability of pilots to control longitudinally unstable airplanes. Some high-performance airplanes normally cruise at supersonic speeds with minimum longitudinal stability so as to reduce trim drag. At subsonic speed, such airplanes enter a regime of longitudinal instability and must rely on some form of stability augmentation in order to fulfill the specified handling-qualities requirements. As a result, the ability of pilots to retain adequate control of the airplane following failure of the augmentation system is of interest. These airplanes also possess relatively small changes in normal acceleration per degree change in angle of attack because of flight at very high altitudes and use of highly swept plan forms. Consequently, the danger of exceeding structural limits as a result of longitudinal divergence is reduced somewhat. Therefore, the effect of lift-curve slope on the tolerable level of stability is also of interest.

The Langley Research Center had a twin-engine light transport airplane in which both the wing flaps and a portion of the elevator could be controlled through an automatic control system, commanded by a nose-mounted vane which sensed the angle of attack. The basic components and concepts of this equipment, which had been designed primarily as a gust-alleviation system, are described in references 1 and 2, respectively. As a result, the longitudinal stability and effective lift-curve slope could be varied independently. The present paper presents a study of the ability of human pilots to control this variable-stability airplane when static stability is varied from values greater than basic-airplane stability to values of negative stability. In addition, concurrent changes in effective lift-curve slope from the positive value of the basic airplane to negative values were obtained to study the effects of reduced lift-curve slopes on the tolerable level of stability.

A simultaneous program was conducted by other investigators at the Langley Research Center on a subsonic jet-propelled fighter airplane which permitted variable-stability studies at greater changes in normal acceleration per degree change in angle of attack. (See ref. 3.) Additional variable-stability investigations are described in references 4 and 5.

SYMBOLS

a_n	normal acceleration, g units
C_{L_α}	derivative of lift coefficient with respect to angle of attack
C_{m_α}	static stability derivative
$\bar{c}$	mean aerodynamic chord of wing, ft
g	acceleration due to gravity, ft/sec^2
K	system gain, ratio of flap deflection to angle of attack, measured by the angle-of-attack vane
K_1	ratio of auxiliary-elevator deflection to main-wing-flap deflection, $\delta_{e,a}/\delta_f$
L	lift, lb
S	wing area, sq ft
$t_{1/2}$	time to damp to half amplitude, sec
t_2	time to double amplitude, sec
V	velocity along flight path, ft/sec
$\Delta\alpha$	incremental angle of attack away from trim, deg
α_0	trim angle of attack between X-body axis and velocity vector, deg
α	angle of attack, deg
δ_c	deflection of pilot's control, deg
δ_e	deflection of main elevator, deg
$\delta_{e,a}$	deflection of auxiliary elevator, deg

δ_f deflection of main wing flap, deg

δ_v deflection of angle-of-attack vane, deg

$\dot{\theta}$ pitching velocity, radians/sec

θ angle of pitch, deg

ρ air density, slugs/cu ft

APPARATUS

The twin-engine light transport airplane used for the present investigation was initially modified to incorporate a gust-alleviation system which is described in reference 1. The test airplane is presented in figures 1 and 2 and the system of axes is shown in figure 3. The control-surface modifications consisted of a main trailing-edge flap which was connected to the aileron for maximum lift-changing capability, a short auxiliary flap at the wing root for downwash control, and an auxiliary portion of the elevator to counteract the wing pitching moment caused by deflections of the main wing flap. The auxiliary downwash flap remained in a neutral position for the present tests. The auxiliary flap and auxiliary elevator were mechanically geared to the main flap. These surfaces were operated by an automatic control system as a function of the deflection of the angle-of-attack vane. A block diagram of the major components of the automatic control system is shown in figure 4.

Longitudinal inputs to the system were initiated by the pilot's control which was connected directly to the main elevator. Lateral control was furnished by the displacement-type autopilot of the original airplane. The effective airplane lift-curve slope decreased as the gearing between the flap and the vane, or system gain, was increased. This system gain commanded the wing flap to deflect upward as the nose of the airplane pitched upward, a condition which decreased the change of airplane lift with angle of attack. The slope of the lift curve ranged from that of the original airplane at zero system gain to a slightly negative slope at the maximum system gains. Although it would have been desirable to maintain a constant value of C_{L_α} while testing a series of values of C_{m_α}, these conditions could not be conveniently provided in flight because of the manner in which the control system moved the surface controls.

The linkage ratio between the auxiliary elevators and the wing flaps was mechanical and could be set only while the airplane was on the ground.

Each linkage ratio is referred to throughout the paper as a flight-test configuration. The gain between the vane and flaps, referred to throughout the present paper as the system gain, was electrical and could be varied in flight. The output of the electronic amplifier which controlled the system gain was erratic below a flap command of about 0.5° per degree of angle of attack. Data for the present study were obtained at gains higher than 0.5° per degree and, therefore, were not affected.

TESTS

The basic characteristics of the variable-stability airplane, which was originally used for gust alleviation, are presented in reference 1. Flight tests were conducted at a 5,000-foot altitude, and inputs were initiated from trim flight. A total of five flights were made embracing five different settings between the auxiliary elevator and the main wing flap. Figure 5 presents flight data of the variation of $C_{m_{\alpha}}$ with system gain K for the five flap-elevator configurations, along with the variation of $C_{L_{\alpha}}$ with K which was relatively insensitive to changes in the fixed, mechanical flap-elevator gearing. Pulse and step elevator inputs were made at each stability condition of the investigation to establish stick-free and stick-fixed stability. Straight and level flight, speed and altitude changes, and slow and rapid pullups, pushdowns, and turns were also performed at each stability condition to aid pilots in forming opinions regarding flying qualities of the airplane. All maneuvers except the deliberate speed changes were initiated at the trim airspeed of 135 knots.

The rating system shown in table I was used to classify pilot opinions. During each flight the gain between the vane and the flaps was increased incrementally from zero to the highest level that could be tolerated for that configuration. The flap along most of the wing trailing edge could deflect between -20° and 20°; and for the flight-test data to be of value for this study, the flap had to remain within this range and not reach full deflection. If the flap moved against the stop at a deflection of 20°, the airplane ceased to function as a variable-stability airplane; instead, it regained its basic airframe stability. This feature provided a factor of safety at high levels of instability. However, this limit on flap travel also reduced the amount of control input that could be used at high levels of system gain for which several degrees of wing-flap deflection were commanded for each degree of angle of attack; and when instability existed at this condition, only very rapid control corrections could be studied.

The lift capability of the test airplane always decreased in a consistent manner when the static stability of the airplane was changed from its basic value. However, since it was possible to change static stability at a different rate for each flight, a range of stability could be tested at any specific value of reduced lift-curve slope. In general, the range of static stability that was possible at each level of lift capability increased as the lift-curve slope of the modified airplane decreased. This decrease in lift capability was an inherent feature of the control system and was incidental to the present investigation. When C_{L_α} was zero, the airplane could be rotated in pitch without changing lift from the 1 g trim condition. It is interesting to note that these data obtained at linearly decreasing lift capabilities afford an insight to the response of proposed high-altitude or reentry configurations that may evolve in the future employing either low lift or negative lift-curve slopes for extremely high-speed flight operations on the fringes of aerodynamic control. This concept is described in reference 6.

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RESULTS AND DISCUSSION

Figure 5 shows how the five configurations investigated in the present study affected C_{m_α} as the amount of wing-flap deflection commanded by each degree of deflection of the angle-of-attack vane was increased. The derivative C_{L_α} decreased with increased system gain and was insensitive to changes in flap—auxiliary-elevator configurations. The gearing which resulted in a deflection of -0.475° of the auxiliary elevator for each degree of wing-flap deflection and would have maintained the basic-airplane static longitudinal stability at all system gains is shown as a dotted horizontal line in figure 5. This setting was not tested in the present study. As system gain was increased, one of the five configurations that was tested increased C_{m_α} and the other four flight configurations decreased C_{m_α}.

The data of the present study were determined from flight records. The results are presented in the form of values of C_{m_α} and C_{L_α} in order to utilize further the data of reference 1 in predicting flap-elevator effectiveness and in checking the dynamic response of the system.

Configurations I and II were highly stable and were undesirable at high system gains only from the standpoint of low or negative lift-curve slopes. When the gain was such that the effective lift-curve slope was zero, the airplane could be rotated through moderate angles in pitch without varying the 1 g lift, which would make a change in flight path impossible. Such an experience might be anticipated in space flight beyond the realm of aerodynamic-control effectiveness.

Neutral stability and negative lift-curve slope were possible at high system gains with configuration III, and low static stability coupled with airplane lift response in the opposite direction to that anticipated by the pilot made this configuration intolerable. The pilots agreed, however, that control of a stable airplane with a negative lift-curve slope would be acceptable; and once the pilot was accustomed to reversed lift force, tolerability would then be based purely on static-stability considerations.

Negative static stability was possible with the final two flap-elevator configurations (IV and V) tested, and neutral stability was possible at respectively lower system gains so that sufficient lift capability remained to allow for the evaluation of control quality with a customary flight-path response similar to that of a normal airplane. Neutral static stability in the presence of a moderate lift-curve slope was tolerable, but marginal. The maximum gain used with configuration IV produced negative stability half the original stable value, based on the basic-airplane lift ability, and this high degree of instability was coupled with zero C_{L_α}. This condition was extremely undesirable.

Evaluation of the variable-stability airplane for a wide variation in static stability was possible with the flap-elevator gearing of configuration V without prohibitive loss in lift capability. (See fig. 5.) As a result, this was the optimum configuration for determining how much instability a human pilot could tolerate and still maintain a reasonable amount of control over the airplane without stability augmentation. At the highest system gain used with this flight-test configuration, maximum negative static stability was the same as the maximum value reached with the previous configuration (C_{m_α} = 0.270), and almost half of the basic-airplane lift capability remained. Figure 6 presents a time history of the response of configuration V for this condition, along with a comparison time history of a test made at the same value of C_{L_α} but at a stable value of -0.325 for C_{m_α} with configuration III. With this extreme condition, when disturbed from trim the airplane with configuration V diverged very rapidly in pitch, and lift increased accordingly. Full control reversal - initiated 1 second after the pilot initiated a slight disturbance to configuration V at this condition with a value of 0.270 for C_{m_α} - failed to arrest the resulting violent divergence in pitch before airspeed had decreased from a trim speed of 135 knots to a true airspeed of 110 knots and before the wing flap had reached the 20° deflection limit. System gain for this condition was 3° of flap deflection per degree of deflection of the angle-of-attack vane, and the flap was limited at an incremental angle of attack of 7°. Notwithstanding the limited range of control effectiveness, this level of stability was obviously intolerable and dangerous and was beyond human-pilot controllability.

Intermediate stability levels between neutral stability and the extreme condition at which C_{m_α} = 0.270 were tested with configuration V to define the tolerable limit. As stated earlier, neutral stability presented no problem. As stability was reduced to an unstable value of C_{m_α} of 0.05, the airplane was more difficult to fly, particularly in rough air. With a further reduction in static stability to a value of 0.10 for C_{m_α}, and with half the basic-airplane lift capability, the pilots could perform mild maneuvers at trim speed without difficulty as long as control inputs were smooth and were initiated as soon as the airplane began to diverge. It became increasingly apparent, however, that the tolerable limit for abrupt control disturbances or slow-speed flight in the presence of rough air had almost been reached. The pilots deemed this condition acceptable for a jet penetration and possibly a gradual, high-speed, straight-in landing approach. At a value of C_{m_α} of 0.16, small excursions from trim could be corrected only by rapid control reversal made before the ensuing divergence had reached a high rate of pitch. If the speed were allowed to decrease to 110 knots before the disturbing input was initiated, the airplane could not be recovered from a nose-high position with full forward control before flap limiting caused the return to basic airframe stability. Little doubt existed as to the inadequacy of control for this underspeed condition, and it was rated unacceptable even for emergency use. In the opinion of the pilots participating in the present study, a value of 0.16 for C_{m_α} exceeded the limit of instability consistent with overall human-pilot control of the present system. The tolerable limit was placed between values of 0.10 and 0.16 for C_{m_α}.

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Figure 7 presents a summary plot of C_{L_α} against C_{m_α} for the present investigation and identifies the trend of each flight and flap-elevator configuration studied. The trends radiate from the basic-airplane value at zero system gain and terminate at the value obtained with the maximum system gain utilized for each flight. Each combination of C_{L_α} and C_{m_α} tested in flight is plotted and keyed to pilot opinion by a symbol representing a pilot-opinion rating from table I. The same pilot-opinion symbols from flight to flight could be used to define a family of isoopinion curves in terms of values of C_{L_α} and C_{m_α}. One such curve, the isoopinion curve that establishes the border between acceptable and unacceptable combinations of C_{L_α} and C_{m_α} for adequate control of the airplane following the loss of stability augmentation, is shown as a dashed line in figure 7.

When the negative lift-curve slopes were encountered at high system gains with the first two configurations shown in figure 7, the pilots rated the unexpected reversed control effectiveness and seemingly unstable response as unsatisfactory. Then, as the third configuration produced this reversal in lift response at neutral stability, the condition was rated unacceptable. As stated previously, it is felt that if a vehicle were operating consistently with negative lift-curve slopes, pilots would subscribe to them after a brief period of familiarization. The concept of an aerodynamic reentry vehicle which would use this principle is described in reference 6. In the present tests, the fact that the lift-curve slopes changed from positive to negative, had small values, and were experienced so briefly at each flight condition contributed to the adverse rating given to negative lift-curve slopes.

Figure 8 shows the data of the present investigation in terms of the ability to change normal acceleration for each degree of angle of attack plotted against inverse values of the time required to double (or halve) the pitch amplitude. Figure 8 deals with the dynamic response of the airplane in various flight-test configurations, whereas figure 7 dealt with just the static stability characteristics; figure 8, therefore, summarizes the results of the present investigation in a form that may be compared with the results of similar studies. Each symbol denoting pilot-opinion ratings has a corresponding symbol in figure 7. Conditions near neutral dynamic stability $\left(1/t_2 = 1/t_{1/2} = 0\right)$ and with half the original-airplane lift slope were tolerable. For increasingly unstable flight which doubled the amplitude of the airplane response in less than 2 seconds $\left(1/t_2 = 1/2\right)$, the human-pilot control ability deteriorated very rapidly. Negative effective lift-curve slopes were obtained at system gains commanding flap deflection in excess of 5° per degree of angle of attack. This level of gain was not utilized with configurations IV and V, which produced unstable flight; negative values of a_n/α in figure 8, therefore, are on the stable side of neutral stability.

In addition to the present investigation, a simultaneous program was conducted by other personnel at the Langley Research Center by utilizing a subsonic jet-propelled fighter airplane with provisions for varying the center-of-gravity position. (See ref. 3.) One of the two pilots who conducted the flight program described herein also conducted the program with the subsonic fighter and was in a position to compare the two on the basis of his ability to arrest an unstable divergence. Notwithstanding the fact that the subsonic fighter possessed much higher normal-acceleration capability than the airplane used in the present study, plus the fact that there was a wide variation in the amount of normal acceleration per degree change in angle of attack produced by the airplane used in this study, the definition of the tolerable-stability criterion for human-pilot control was essentially the same in both cases in terms of divergence times. It had been anticipated that this inherent decrease in a_n/α would have a favorable effect upon the tolerability of the dynamic response of the present test airplane; however, this was not the case.

Additional flights simulating configurations IV and V were made by two pilots other than the two pilots who conducted the basic flight program in order to obtain more pilot-opinion ratings. The comments of these pilots paralleled those of the pilots who obtained the data presented herein and substantiated their evaluation of the various stability levels of the test.

CONCLUSIONS

Pilot opinions and flight results of an investigation made with a variable-stability airplane at relatively low values of normal acceleration per degree change in angle of attack indicate that the upper tolerable limit of unstable static stability derivative of the airplane is between 0.10 and 0.16. In terms of dynamic-response time, an unstable airplane that requires from 2 seconds to the infinite time of neutral stability to double the amplitude in pitch is marginally tolerable for emergency operation. An unstable airplane that diverges to double pitch amplitude in less than 2 seconds is either marginal or unacceptable as the time to diverge grows shorter. Decreasing the amount of normal acceleration per degree change in angle of attack does not alter the definition of the tolerable-stability criterion for human-pilot control in terms of the dynamic response of the airplane which defines the time to diverge.

In the operation of the automatic control system of the test airplane, an effect that was incidental to the variation of longitudinal stability was the inherent decrease in lift-curve slope as the command to the wing flap was increased. A conclusion unique in the present tests is that neutral or very slightly unstable static stability is tolerable for emergency operation as long as some airplane lift-curve slope prevails. After a brief familiarization period, control of a stable airplane with a negative lift-curve slope would be acceptable.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., November 5, 1959.

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TABLE I.- PILOT-OPINION RATING SYSTEM

Type of operation	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[a]	Doubtful	Yes
None	Unacceptable	7	Unacceptable even for emergency condition[a]	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
---------	Impossible	10	Did not get back to report	No mission	--------

[a]Failure of a stability augmenter.

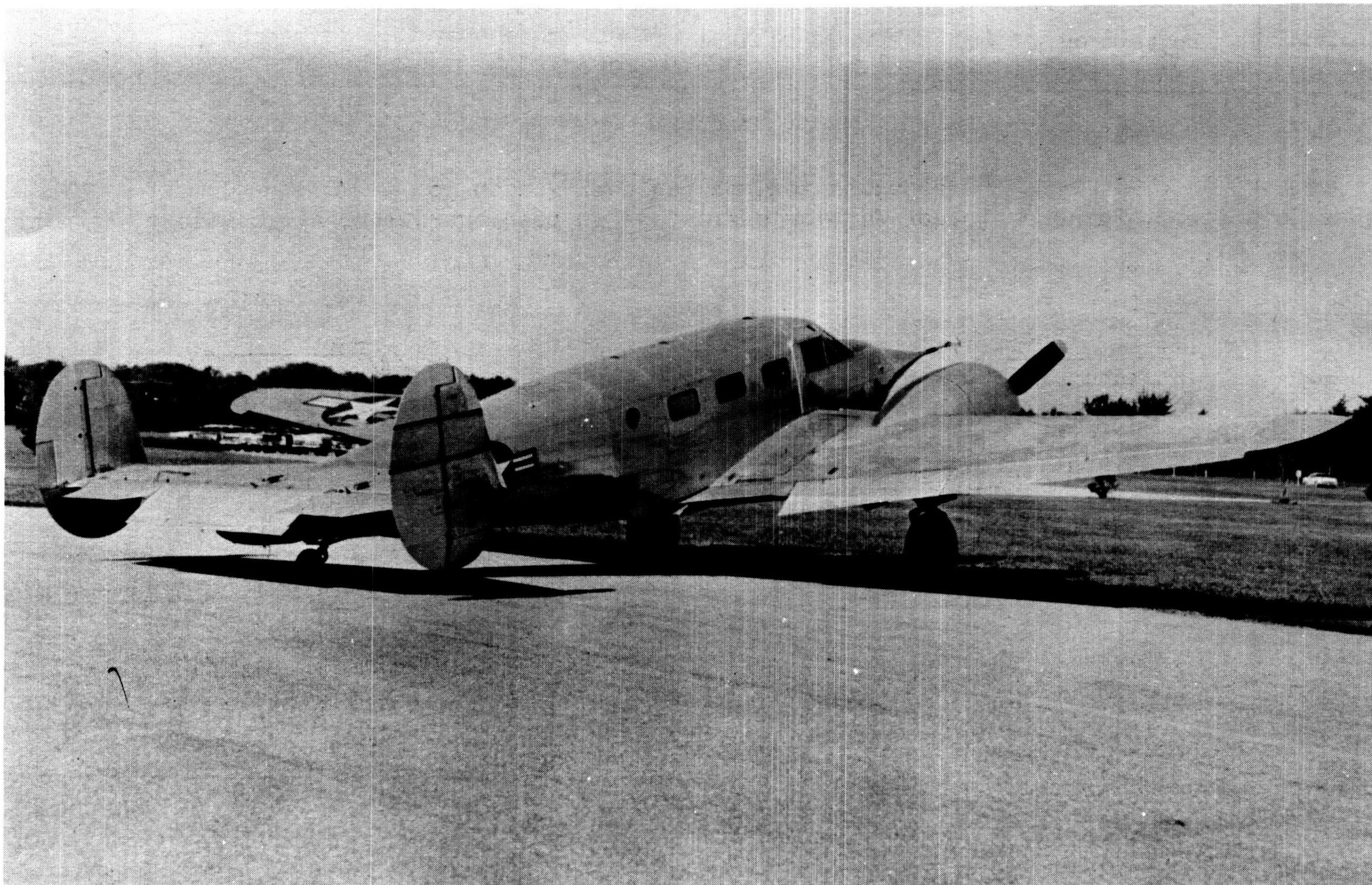

Figure 1.- Photograph of test airplane. L-58-4005.1

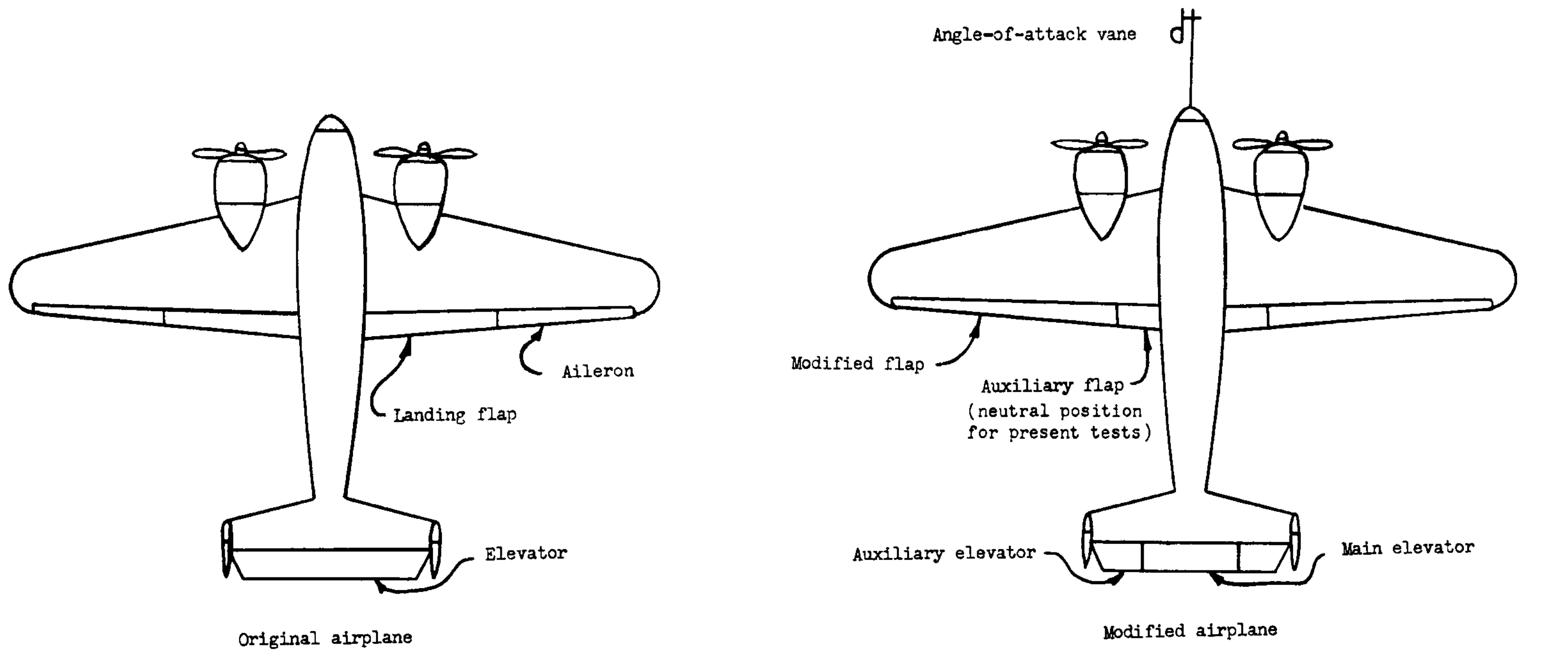

Figure 2.- Sketch of test airplane used as variable-stability vehicle showing location of angle-of-attack vane and control surfaces.

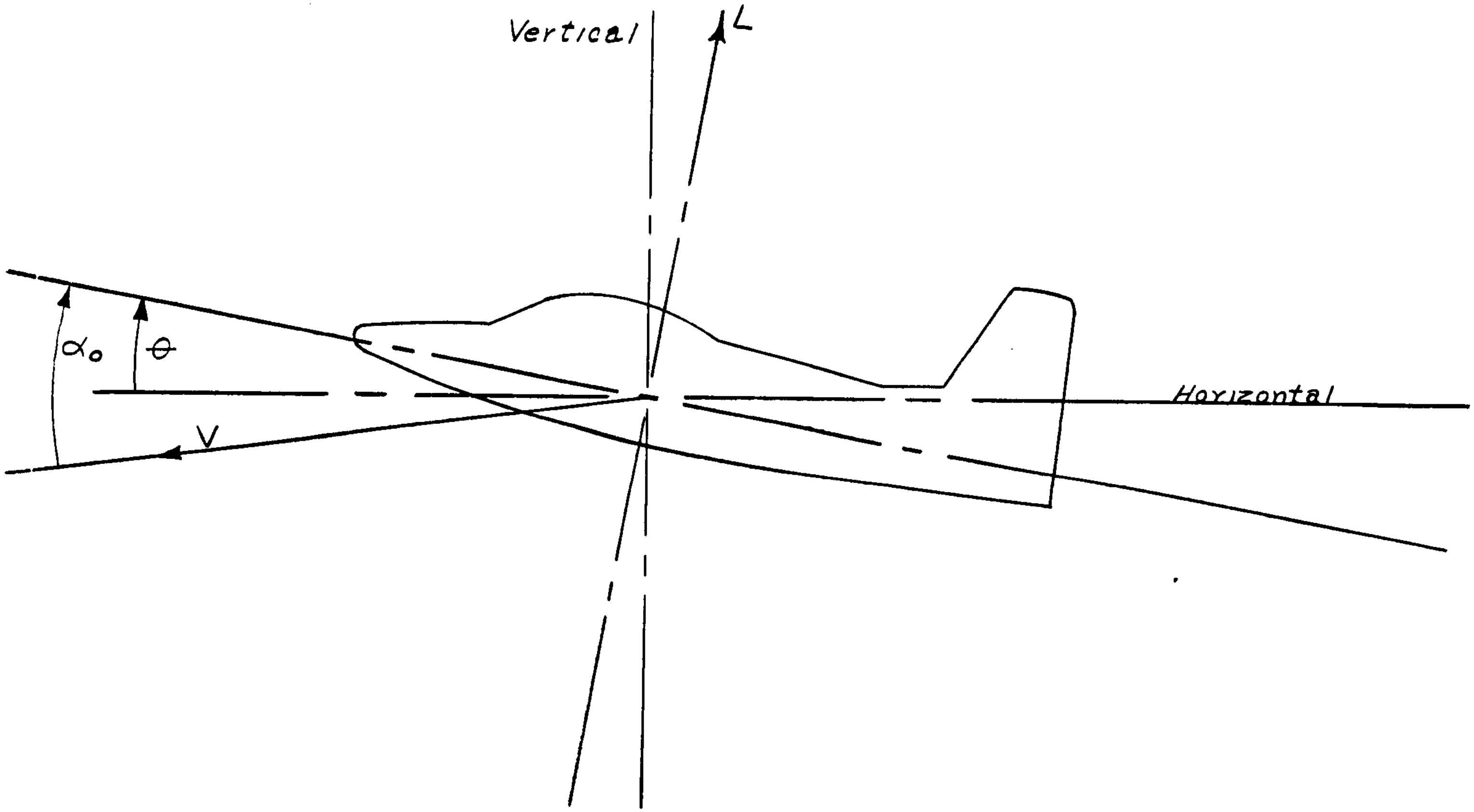

Figure 3.- Axis system and positive directions used in variable-stability study.

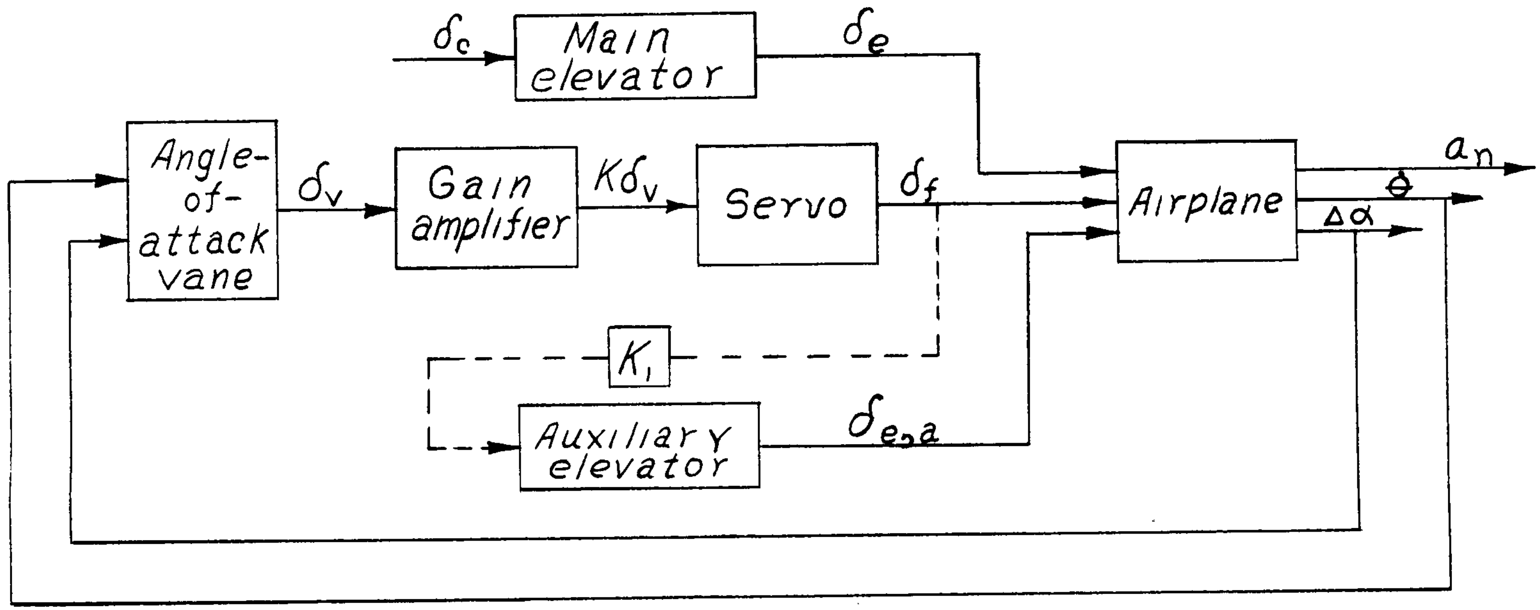

Figure 4.- Simplified block diagram of automatic control system of variable-stability airplane.

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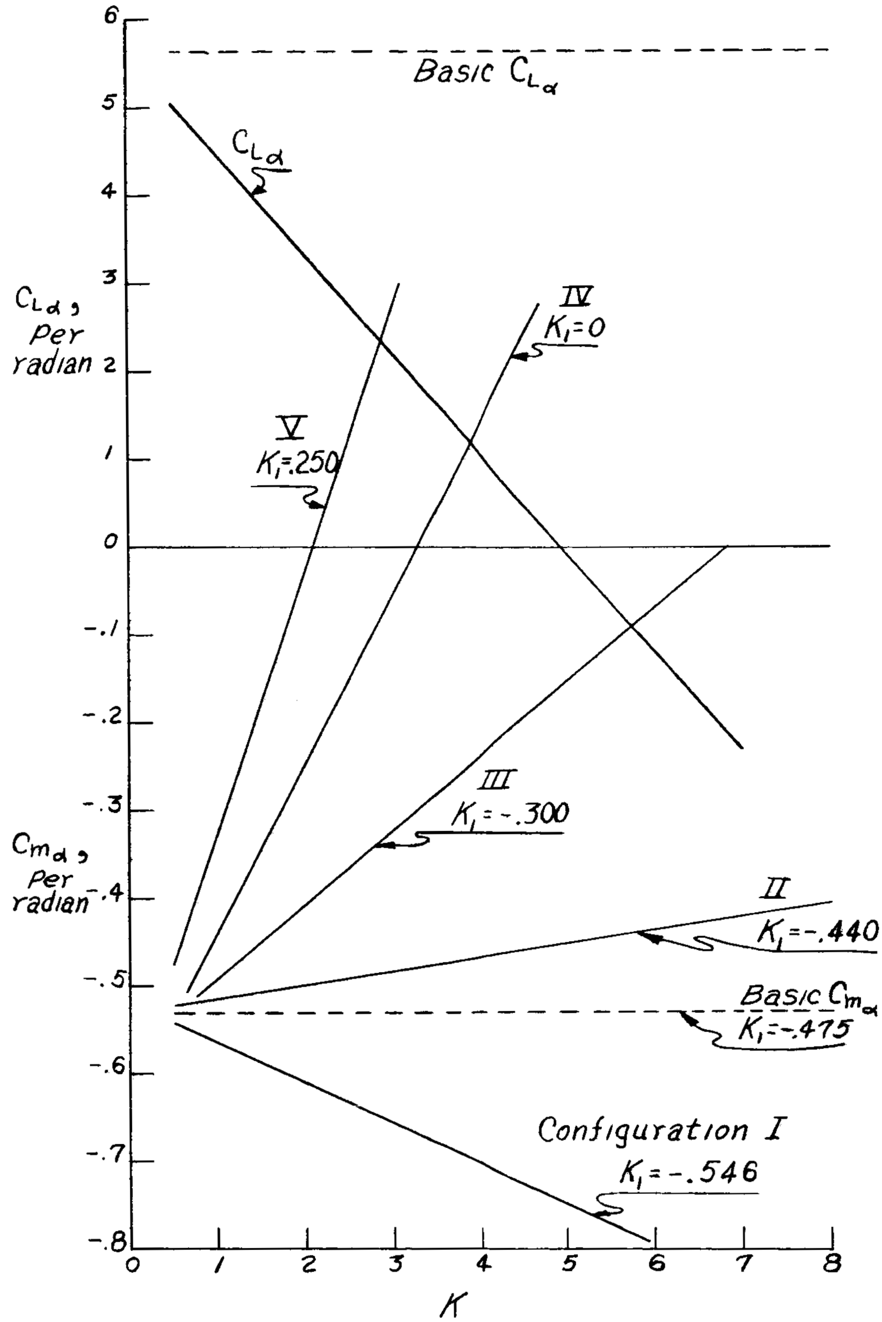

Figure 5.- Variation of C_{L_α} and C_{m_α} with system gain K for the five flap-elevator configurations, showing the additional effect of elevator gearing K_1 on C_{m_α}.

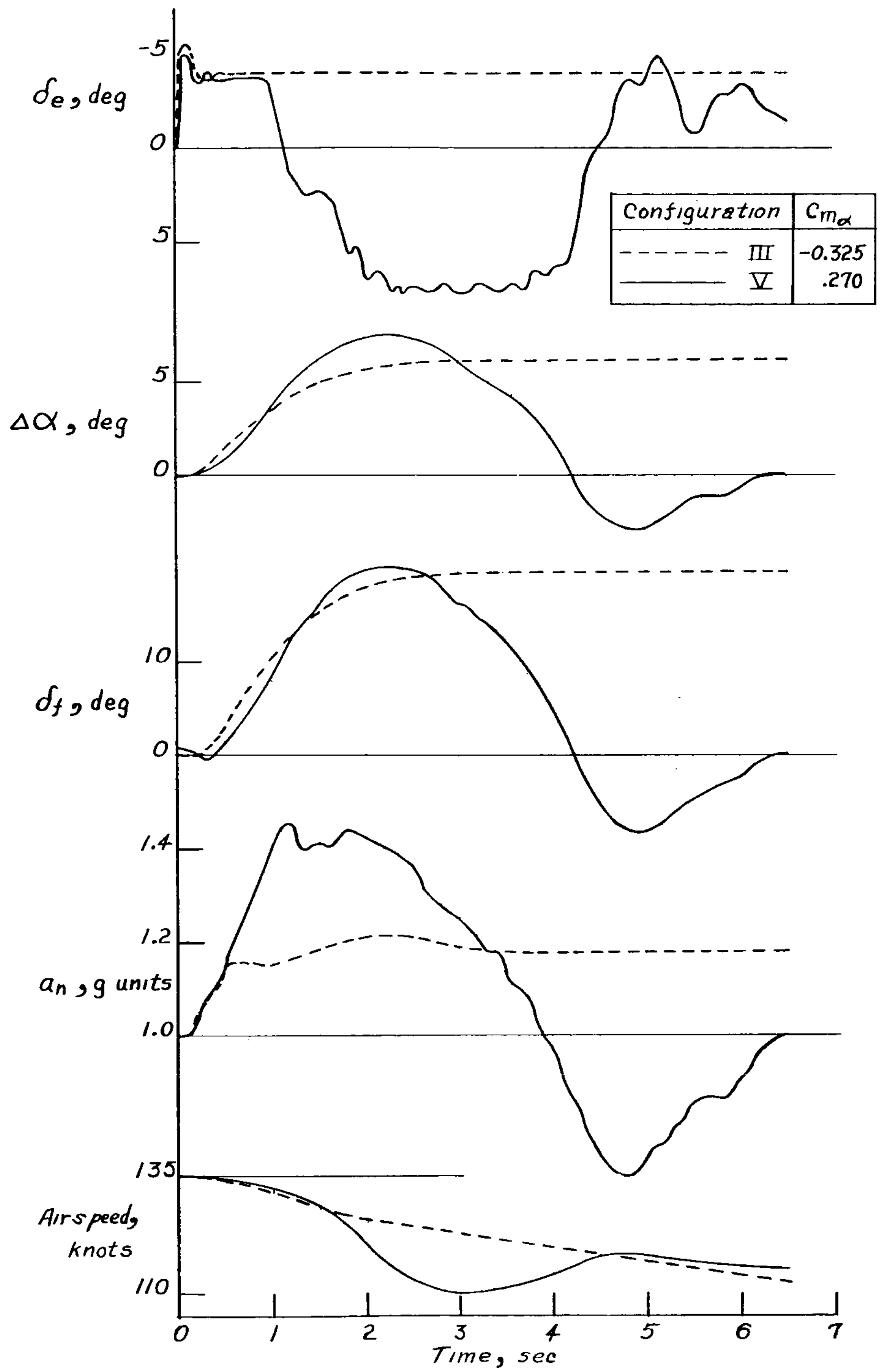

Figure 6.- Response of the variable-stability airplane to a step elevator deflection. $C_{L_\alpha} = 2.2$ per radian.

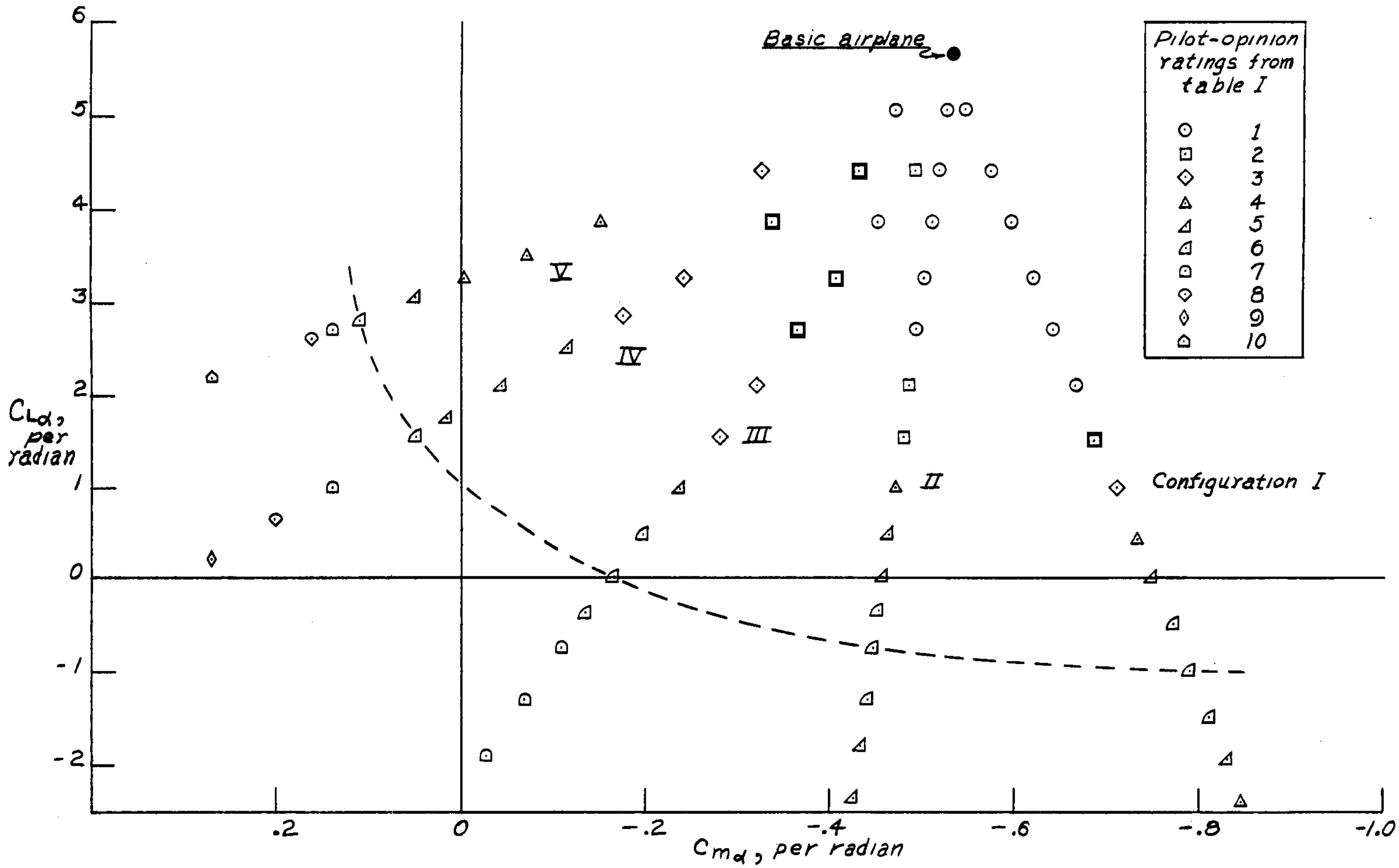

Figure 7.- Pilot-opinion ratings of the five configurations at various values of C_{L_α} and C_{m_α}. The isoopinion boundary of tolerability is shown as a dashed-line curve.

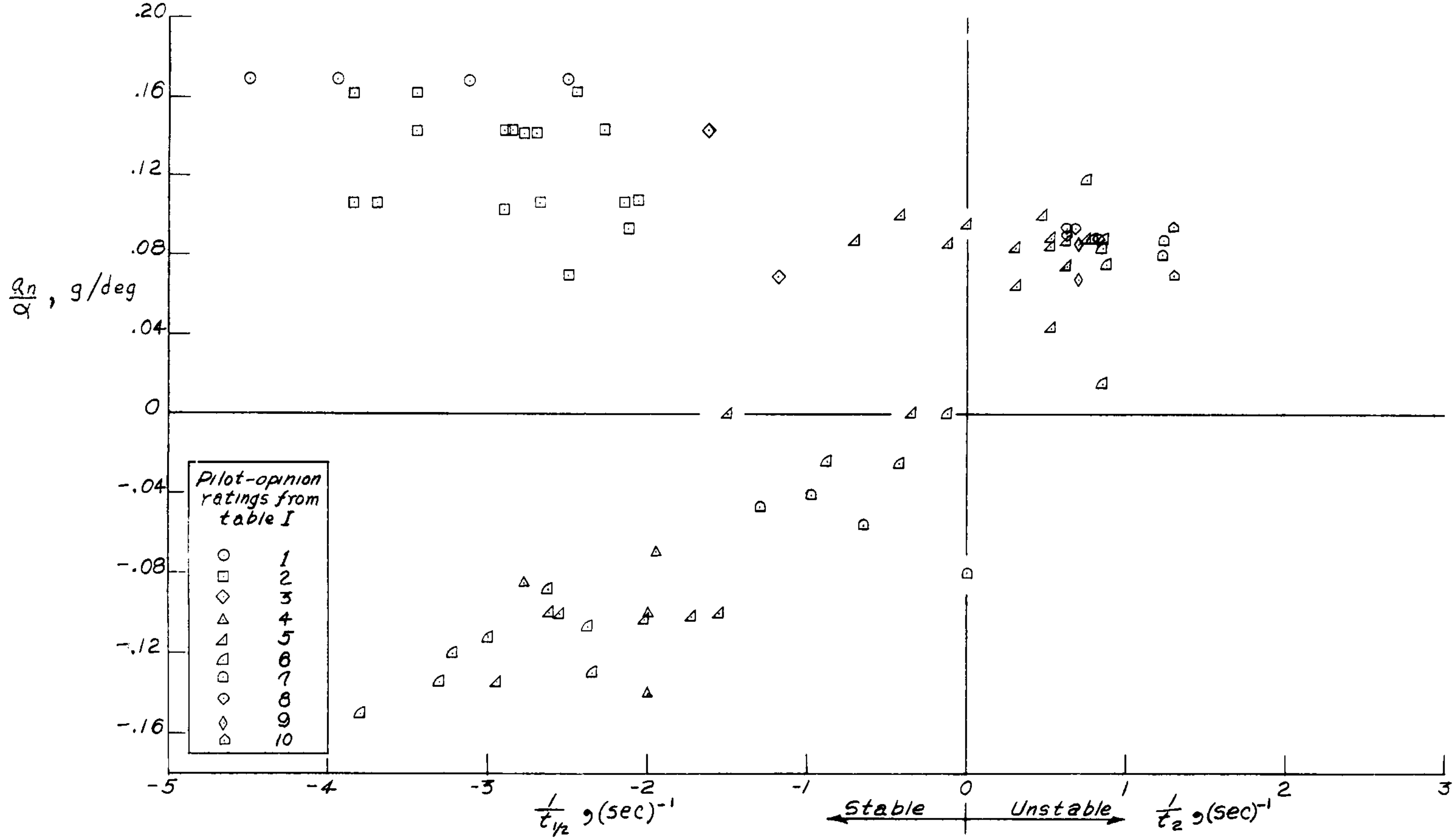

Figure 8.- Normal acceleration per degree change in angle of attack of the test airplane (identified by pilot-opinion symbols) plotted against inverse dynamic response times.

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